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Constraints on maize yield and yield stability in the main cropping regions in China

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ABSTRACT

Understanding the distributions of zones of high/low and stable/unstable recorded maize (*Zea mays* L.) yield, and identifying the constraints on yield and yield stability, is essential for optimized crop distribution and agricultural management to mitigate limitations and improve maize production under climate change. In this study, we collected recorded maize yields and simulated three levels of yield potentials (radiation-temperature yield potential Y_p, climatic yield potential Y_{pw} and soil-climatic yield potential Y_{pws}) with the Agricultural Production Systems sIMulator (APSIM-Maize) from 1981 to 2010 in the three main cropping regions in China [the North China spring maize region (NCS), the Huanghuaihai summer maize region (HS), and the Southwest China mountain maize region (SCM)]. The distributions of four categories of maize yield and yield stability zones, and limitations by precipitation, soil and technology & management on average yield, yield stability and total production were analyzed. The county-level average recorded yields during the period under study were 4624.26 kg ha^{-1}, 4718.32 kg ha^{-1} and 3880.44 kg ha^{-1} in NCS, HS and SCM, respectively. Coefficients of variations (CV) for recorded yields were 0.40, 0.30 and 0.27 in NCS, HS and SCM, respectively. Based on comprehensive analysis of both average yields and CV values, we divided the main maize cropping areas into four zone categories: those with high and stable yields (high-stable zone), those with high and unstable yields (high-unstable zone), those with low and stable yields (low-stable zone), and those with low and unstable yields (low-unstable zone). Comparison of Y_p, Y_{pw}, Y_{pws} and Y_a at the county level, among the three regions, revealed that precipitation was the most important limiting factor on both averages (56%, 9436.97 kg ha^{-1} and 53%, 8114.21 kg ha^{-1}) and CVs (0.42 and 0.39) of yield in all four zone types in NCS and HS. On the other hand, technology & management was the most important limiting factor in SCM (39%, 3934.87 kg ha^{-1}). Total maize productions were reduced by 47.6% and 52.7% by precipitation in NCS and HS, respectively. Nevertheless, the limiting effect of soil was lower than that of technology & management in NCS, while it was higher in HS. In SCM, technology & management was the most important limiting factor (1295.72×10^4 t and 39.3%), followed by precipitation (613.80×10^4 t and 18.6%) and soil (219.62×10^4 t and 6.7%). In the three main cropping regions, the limiting effect of each factor on total productions in high-stable zone was the highest among all four zone types. Our results could be used to provide a theoretical basis for targeted climate change adaptation policies to improve maize yield and yield stability in China. In addition, our results may serve as a reference for other maize cropping regions in the world.

1. Introduction

China is the second largest maize (*Zea mays* L.) producer and consumer in the world, accounting for 19.15% and 21.42% of total harvest areas and production in the world in 2014 (FAO, 2014). Between 2004 and 2012, maize planting areas and total production increased in a near-linear fashion by 45.2% and 79.7%, respectively (Zhao and Wang, 2013). Therefore, it is strategically important to promote maize production for ensuring China's national food security (Meng et al., 2013; Zhao and Wang, 2013). However, statistical analysis has shown that climate change is increasingly affecting maize yields worldwide (Challinor et al., 2014; Gabaldón-Leal et al., 2016; Lobell et al., 2011; Rose et al., 2016), and effects of climate change on maize yields have also been reported in China (Liu et al., 2012; Tao et al., 2015; Wang et al., 2014a, 2014b). Because of differences between local environmental and productive conditions, it is essential to clarify the constraints by different limiting factors on maize yield in each region, and make targeted adaptations to meet future food demands.

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Under current agricultural production systems, crop yield is dependent on solar radiation, precipitation, temperature, soil physical properties and fertility, and management decisions such as hybrid selection, planting date, and inputs (fertilizers and irrigation) (Kucharik, 2008). Yield gaps between yields under different limiting factors and the recorded yield reflect the limiting effects by the corresponding factors (Cassman et al., 2003; Liu et al., 2016a). The radiation-temperature yield potential (Y_p) is the yield limited only by solar radiation and temperature under optimal soil conditions and management, and without yield losses due to biotic and abiotic stress. Y_p should be the maximum yield which could be reached by a crop variety in any given environments, because the solar radiation and temperature are difficult to control under field conditions (Evans and Ficsher, 1999; Grassini et al., 2011). Accurate estimates of Y_p are essential for assessing regional crop production capacity on existing farmland, given the best management practices and possible improvements in the future (Liu et al., 2017, 2016a). However, potential conditions cannot be realized in the field for the perfect management of crop and soil factors that influence plant growth and development throughout the crop growth cycle (Lobell et al., 2009). Moreover, between Y_p and farmers' recorded yield (Y_a), there may be several yield levels due to one or more limiting factors. Yield potential under water-limited conditions (climatic yield potential Y_{pw}, maximum yield with no other manageable limitation than water supply) and actual soil physical condition (climatic-soil yield potential, Y_{pws}) are two important yield potential levels, since most maize fields are rain-fed and abundant in soil physical properties in China (Liu et al., 2017). Comparing the limiting factors on yield potentials and actual yield (Table 1), the yield gaps between Y_p and Y_{pw}, Y_{pw} and Y_{pws}, Y_{pws} and Y_a can reflect the limitations of precipitation, soil and technology & managements on maize yield.

Crop modeling is an effective tool to simulate yield potentials and to analyze yield gaps, which has been applied in previous studies on maize in China. Liu et al. (2016a,b) investigated the maize yield gaps between potential yields, attainable yields, and potential farmers' yields simulated by the APSIM-Maize model, and recorded farmers' yields in Northeast China, and identified yield gaps caused by non-controllable, agronomic, and socioeconomic factors under conditions of climate change. Meng et al. (2013) compared maize yield potential simulated by the Hybrid-Maize model and recorded maize yields published in the literature from field experiments and farm survey data in the four maize agro-ecological regions of China. Liu et al. (2017) used the agro-climatic zones and the reference weather stations buffer zones, together with the Hybrid-Maize model to estimate maize Y_p in the four maize-growing-regions of China under both irrigated and rain-fed conditions. In addition, farm surveys (Liang et al., 2011) and remote sensing (Zhao et al., 2015a,b) were used to estimate the yield potential and yield gaps in maize cropping regions in China.

In addition, increased probability, frequency, and severity of possible extreme events or disasters can also cause considerable damage to crops and food systems infrastructure (Lesk et al., 2016). Maize yield stability would also influence food security (Liu et al., 2005). Therefore, it is also necessary to understand yield-stability gaps caused by different factors (Guan et al., 2017; Katz and Brown, 1992; Rosenzweig et al., 2001). However, most previous studies have focused on the average yield gap; while, few studies have researched yield-stability gaps and total productions. In this study, the recorded county-level maize yields and cropping areas were collected in the main cropping regions from 1981 to 2010. In addition, three levels of yield potentials under different limiting factors (Y_p, Y_{pw}, and Y_{pws} in Table 1) (Ma, 1988; Wang, 1987) were simulated using the Agricultural Production Systems sIMulator (APSIM-Maize). The objectives of this study were to: (1) investigate the distributions of four types of maize recorded yield and yield stability zones and (2) quantify the constraints of precipitation, soil and technology & management on maize yield, yield stability and the total production in each region during the study period. The results of this research could be used to provide a theoretical basis for targeted climate change adaptation policies to improve maize yield and yield stability in China. In addition, our results may serve as a reference for other maize cropping regions in the world.

Table 1
The yield gradations and their limiting factors.

Yield level	Limiting factors
Radiation-temperature yield potential (Y_p)	Radiation, temperature
Climatic yield potential (Y_{pw})	Radiation, temperature, precipitation
Climatic-soil yield potential (Y_{pws})	Radiation, temperature, precipitation, soil
Actual yield (Y_a)	Radiation, temperature, precipitation, soil, technology & management

2. Materials and methods

2.1. Study areas and climate data

In China, the North China spring maize region (NCS), the Huanghuaihai summer maize region (HS), and the Southwest China mountain maize region (SCM) account for more than 90% of the maize growing areas (Wang and Li, 2010). In the three main cropping regions, quality controlled historical climate data from 364 meteorological stations from 1981 to 2010 were obtained from the China Meteorological Administration climate data-sharing service system. Annual growing degree-day (GDD) was calculated for each station. We used the inverse distance weighting (IDW) method in ArcGIS software to interpolate GDD within the 20th percentile for stations across the three regions. Areas with a growth degree-day greater than 2100 °C·d (maize can be planted) (Gong, 1988; Liu et al., 2010) were selected as study areas in Fig. 1. In total, 331 meteorological stations were located in the research area and listed in Fig. 1, which were used to simulate the three levels of yield potentials (Y_p, Y_{pw} and Y_{pws}).

2.2. Recorded yields and cropping areas

The recorded maize yields and cropping areas in each county were collected from the 'Agricultural Statistical Yearbook' maintained by the Ministry of Agriculture of China in the main cropping regions in China from 1981 to 2010. Because the recorded yield was the average value of all the fields in each county, it was used as the county-level average yield in this study. And the region-level average yield was the average value of all the county-level average yield in each region.

2.3. Simulation of yield potentials

The APSIM-Maize model (http://www.apsim.info/apsim/), which can successfully capture interactions between soil water and nutrient dynamics, crop growth, climate, and farm management (Gaydon et al., 2017; Keating et al., 2003), was used to simulate maize yield using historical climate data (1981–2010) under three levels of potential conditions in the main maize cropping regions (Table 1). Maize trial data were collected from 14 Agrometeorological Experimental Stations (6 in NCS, 5 in HS, and 3 in SMC) (Fig. 1) operated by the China Meteorological Administration. Based on the phenological data (including sowing, flowering, and physiological maturity dates), cultivars, soil physical properties in the trial fields, yields, management practices, and climate data from the nearest meteorological stations, APSIM-Maize model was validated for its ability to successfully predict maize growth stages (flowering and maturity) in the three main cropping regions. In addition, simulated yields matched observed yields with a high degree of acceptability (Zhao and Yang, 2018). Depending on the availability of data, one cultivar was selected and calibrated for one/two provinces to obtain province-specific crop coefficients for subsequent model

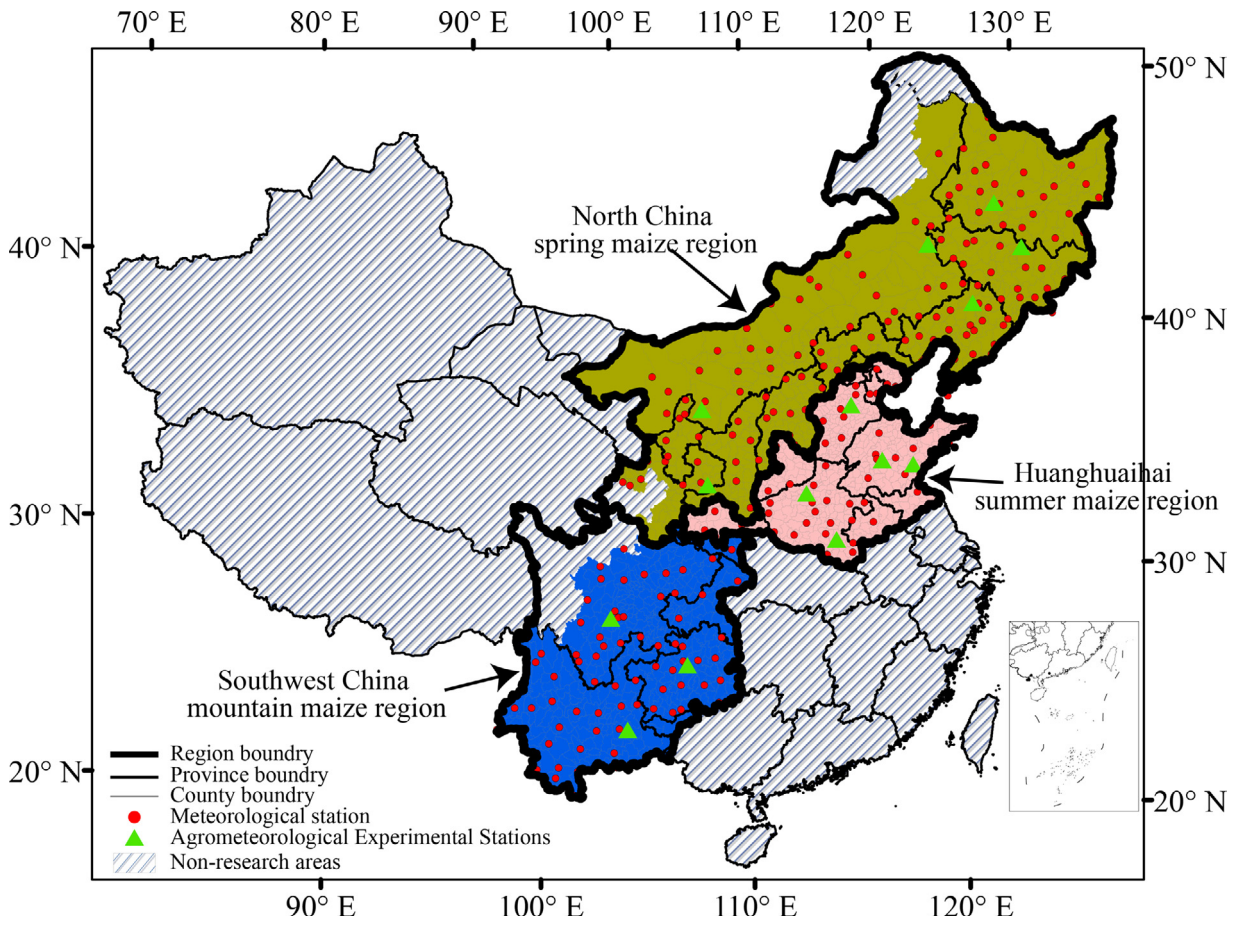

Fig. 1. Locations of the three main maize cropping regions in China and the distributions of meteorological stations in each region.

Table 2
Model setting for the simulation of maize grain yield under potential conditions.

Yield level	Water application	Soil	Sowing date	Density	Nutrient
Y_p	Non-limited	Optimal	Thermal starting date of growing season in NCS and SCM Actual sowing date in HS	Optimal	Non-limited
Y_{pw}	No irrigation	Optimal	Thermal starting date of growing season in NCS and SCM Actual sowing date in HS	Optimal	Non-limited
Y_{pws}	No irrigation	Actual	Thermal starting date of growing season in NCS and SCM Actual sowing date in HS	Optimal	Non-limited

Note: In this table, Y_p, Y_{pw}, and Y_{pws} indicate radiation-temperature yield potential, climatic yield potential, and climatic-soil yield potential, respectively. NCS, HS, and SCM indicate the North China spring maize region, the Huanghuaihai summer maize region, and the Southwest China mountain maize region, respectively.

analysis. To simulate grain yield under the three potential conditions, APSIM-Maize was set following criteria in Table 2:

In regions NCS and SCM, 99% and 89% of the maize cropping area, respectively, was planted with spring maize sown in spring and harvested in autumn. As a thermophilous crop, the maize growing season was defined as the period that was consistently above 10 °C (Zhao et al., 2015a,b). The thermal starting date of the maize growing season was used as the planting date in each year. On the other hand, in the HS region, 99% of maize cropping area was planted with summer maize, and the growing season for winter wheat has to be considered. Therefore, the average observed planting date in the Agrometeorological Experimental Stations in each province was input to the model in HS (Table S1). Nutrient inputs were set as unlimited for all yield simulations. Optimal planting density was set at 86,000 plants per ha based on average surveyed planting densities in 57 high-yielding maize fields in China, by Wang and Li (2013). Planting depth was set at 50 mm and row spacing was set at 60 cm. Based on the soil data from 14 Agrometeorological Experimental Stations, Y_p and Y_{pw} were simulated in each meteorological station. The soil type that can produce the highest Y_p or Y_{pw} was selected as the optimal soil. The actual soil data is from the China Soil Scientific Database, which provided information on soil bulk density (BD), drained upper limit (DUL), 15 bar lower limit(LL15), total nitrogen (N), soil organic carbon (SOC) and pH value (pH) in different soil layers (Zhao and Yang, 2018). The Angstrom formula (Allen et al., 1998) was used to generate appropriate estimates on the amount of daily solar radiation.

2.4. Data analysis

2.4.1. Determination of high/low and stable/unstable zones for maize recorded yields

The average recorded yield in each county from 1981 to 2010 was used to define the high/low zones in the main maize cropping regions. The coefficient of variation (CV) was selected as the index for stable/unstable zones during the study period. CV is the ratio of the standard deviation to the arithmetic mean and can reflect the degree of deviation

within a dataset. The threshold values for high/low or stable/unstable yields were calculated as the average or CV of recorded yield when cumulative frequencies were 50%. Comprehensive analysis of both averages and CVs of recorded yields, geographical distribution and cropping areas percentages of high-stable zones for recorded maize yield in the three main maize cropping regions was conducted.

2.4.2. Constraints of different factors on maize yield and yield stability

The IDW method in ArcGIS software was used to interpolate the averages and CVs of three levels of yield potentials across the entire region. The Zonal tool in ArcGIS was selected to obtain the averages of different yield levels and CVs for yield potentials in each county. According to the definitions of each level of yield in Table 1, the differences in averages and CVs between Y_p and Y_{pw}, Y_{pw} and Y_{pws}, Y_{pws} and Y_a in the same county should give the constraints on yield level and yield stability of precipitation, soil and technology & management in each county.

Constraint of precipitation on yield level ($CYL_{precipitation}$) and yield stability ($CYS_{precipitation}$):

$$CYL_{precipitation} = \overline{Y_p} - \overline{Y_{pw}} \quad (1)$$

$$CYS_{precipitation} = CV_{Y_p} - CV_{Y_{pw}} \quad (2)$$

Constraint of soil on yield level (CYL_{soil}) and yield stability (CYS_{soil}):

$$CYL_{soil} = \overline{Y_{pw}} - \overline{Y_{pws}} \quad (3)$$

$$CYS_{soil} = CV_{Y_{pw}} - CV_{Y_{pws}} \quad (4)$$

Constraint of technology & management on yield level ($CYL_{Technology\ \&\ Management}$) and yield stability ($CYS_{Technology\ \&\ Management}$):

$$CYL_{techno\log y\ \&\ manangement} = \overline{Y_{pws}} - \overline{Y_a} \quad (5)$$

$$CYS_{techno\log y\ \&\ management} = CV_{Y_{pws}} - CV_{Y_a} \quad (6)$$

The ratio of the differences between each level of yield divided by Y_p in each county was selected as the ratio of limitation.

In addition, the limitations by precipitation, soil, and technology & management on maize yield and their stability are given for each county. Based on the recorded maize cropping areas in each county, the limitations by different factors on the total productions could be calculated.

3. Results

3.1. Distributions of high-stable zones for maize recorded yield

Based on recorded maize yield, the county-level average yields from 1981 to 2010 were 4624.26 ± 1425.79 kg ha^{-1}, 4718.32 ± 972.95 kg ha^{-1} and 3880.44 ± 1067.24 kg ha^{-1} in NCS, HS, and SCM, respectively (Fig. 2). The highest recorded yield was found in the western and eastern portion of NCS, with recorded yield of over 8000 kg ha^{-1}. However, the areas with the lowest yields were located in the northwestern region of NCS, and the southwestern region of SCM, with yields below 2000 kg ha^{-1}. In NCS, average yield ranged from 4000 - 7000 kg ha^{-1} in 66.4% of the maize cropping area, and this yield range was found in 79.7% of the cropping area in HS. Although the average recorded yields were greater in HS than in NCS, more cropping fields producing more than 8000 kg ha^{-1} were found in NCS (4.0%) than in HS (0.0%). In SCM, the average yields were 3000 - 5000 kg ha^{-1} in 61.2% of the cropping area.

According to the CVs of maize yield from 1981 to 2010, the areas with the most stable yields were found in the east of HS, where 14.9% of the cropping area showed a yield CVs below 0.20, and in the northwest of SCM, where 17.4% of the cropping area showed a yield CVs below 0.20. Average yield CVs were 0.40, 0.30 and 0.27 in NCS, HS and SCM, respectively. In the three regions, the yield CVs ranged from 0.2 to 0.4 in more than 50% of the cropping area. However, 35.8% of maize cropping areas in NCS had a CV larger than 0.40; while, only 9.4% and 12.6% of the maize cropping area showed a CV greater than 0.40 in HS and SCM, respectively.

Fitting curves of cumulative probability distributions of the averages and CVs of maize recorded yield in the three main cropping regions in China from 1981 to 2010 are shown in Fig. 3. The values corresponding to a cumulative probability of 0.5 were selected as the grading standards for high/low and stable/unstable zones of recorded yields in each cropping region. As such, maize cropping areas could be divided into four types of zones: those with high and stable yields (high-stable zone), those with high and unstable yields (high-unstable zone), those with low and stable yields (low-stable zone), and those with low and unstable yields (low-unstable zone) (Fig. 4).

In NCS, the cropping area ratios in high-stable and high-unstable zones, which were mainly located in the western and eastern regions, included 42.3% (381 × 10^4 ha) and 25.7% (232 × 10^4 ha) of the total area; in contrast, the ratios in low-stable (9.4%) and low-unstable zones (22.6%) were the lowest among the three regions. In HS, the high-stable zone was mainly located in the northern and eastern regions. However, although the cropping area in the high-stable zone (387 × 10^4 ha) and its ratio (45.9%) in HS was higher than that in the other two regions, the areas in the low-unstable zone (mainly located in the southern and western regions, 277 × 10^4 ha) and its ratio (32.9%) were also the highest among the three regions. In SCM, the cropping area in high-stable, high-unstable, low-stable and low-unstable zones were 104 × 10^4 ha, 55 × 10^4 ha, 79 × 10^4 ha and 84 × 10^4 ha with 32.3%, 17.1%, 24.5% and 26.1% cropping area ratios, respectively.

3.2. Constraints by different factors on maize yield and stability

Comparisons of the averages of the estimated Y_p, Y_{pw}, Y_{pws} and recorded Y_a in the counties in the three main maize cropping regions from 1981 to 2010, and the constraints of precipitation, soil, and technology & management on averages and CVs for yield are shown in Figs. 5 and 6.

In NCS and HS, precipitation was the main limiting factor on yield in all four types of yield and yield stability zones. The average limitations by precipitation on yield were 56% (9436.97 kg ha^{-1}) and 53% (8114.21 kg ha^{-1}) in NCS and HS, respectively, and the limiting effects of precipitation decreased from west to east. The highest limitation by precipitation on yield in NCS was found in low-stable zone (39%, 8870.43 kg ha^{-1}); whereas, in HS, the highest limitation by precipitation on yield was found in the high-unstable zone (43%, 9034.84 kg ha^{-1}). The limitations by technology & management on yield (regional average, 17%, 2672.79 kg ha^{-1}) were higher than by soil (regional average, 36%, 1103.83 kg ha^{-1}) in all four zone types in NCS. However, technology & management limited maize yield by 858.55 kg ha^{-1} and 616.66 kg ha^{-1} in low-stable and low-unstable zones in HS, respectively, which was significantly greater than maize yield limitations of 31.43 kg ha^{-1} and 166.56 kg ha^{-1} due to soil limitations. In SCM, the limitation by technology & management was the greatest among the three factors in all four type zones, and the average limitation was 39% (3934.87 kg ha^{-1}). Meanwhile, precipitation limited maize yield by 1335.46 kg ha^{-1}, which was more than the yield limitation imposed by the soil. Yield differences due to precipitation in high-stable (231.99 kg ha^{-1}) and high-unstable zones (798.63 kg ha^{-1}) were smaller than those between low-stable (1958.30 kg ha^{-1}) and low-unstable zones (2037.06 kg ha^{-1}) in SCM.

Similar to the limitations on average actual yield, precipitation was also the main limiting factor on yield stabilities in NCS and HS. Compared with the CV values of Y_p, those of Y_{pw} increased by 0.42 and 0.39 in NCS and HS, respectively. The highest limitations by precipitation on yield stability were found in the low-unstable zone in NCS (0.42), and in the high-unstable zone in HS (0.43). The average limitation values by technology & management on yield stability were 0.17

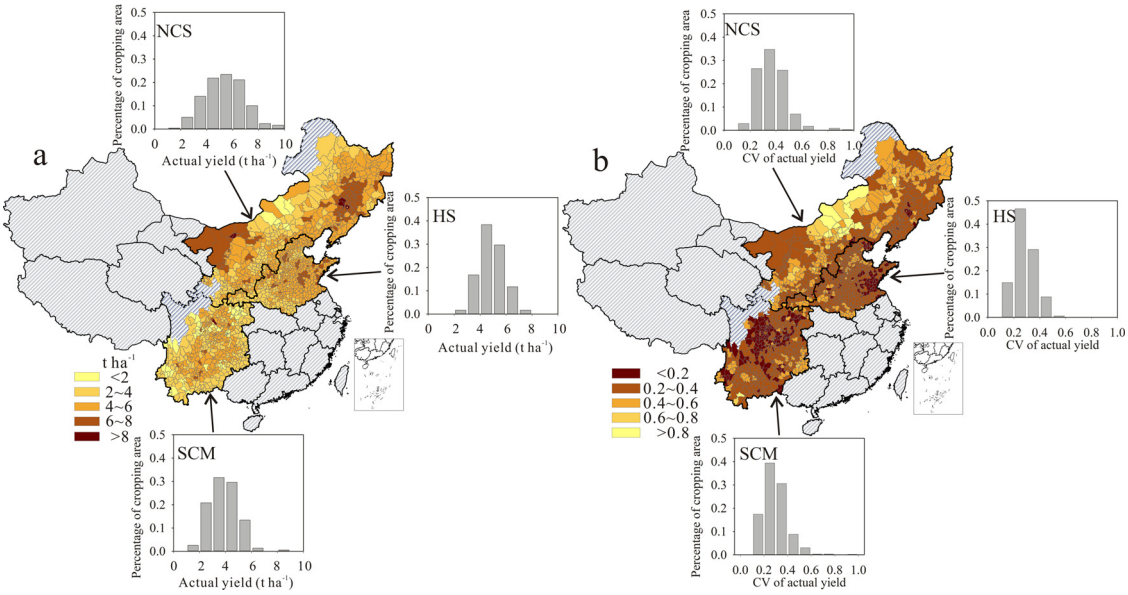

Fig. 2. Spatial distributions and cropping area percentages of averages (a) and coefficients of variations (CVs) (b) of recorded maize yield in the main cropping regions in China during 1981-2010. NCS, HS, and SCM indicate the North China spring maize region, the Huanghuaihai summer maize region, and the Southwest China mountain maize region, respectively.

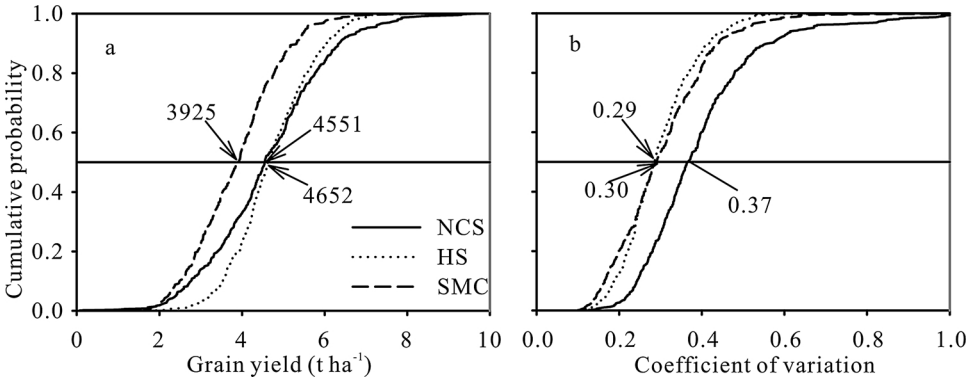

Fig. 3. Cumulative probability distributions of the averages (a) and coefficients of variations (CVs) (b) of recorded maize yield in the three main maize cropping regions in China, 1981-2010. NCS, HS, and SCM indicate the North China spring maize region, the Huanghuaihai summer maize region, and the Southwest China mountain maize region, respectively.

and 0.24 in NCS and HS, respectively; furthermore, technology & management was the second most important limiting factor in both regions, while technology & management was the first most important limiting factor on yield stability (0.13) in SCM. However, precipitation was found to be the second most important limiting factors on yield stability in the high-unstable (0.07), low-stable (0.12) and low-unstable (0.12) zones in SCM; while, the effects by soil and precipitation on yield stabilities were 0.44 and 0.42, in high-stable zones of SCM.

3.3. Constraints by different factors on total maize productions

Coupled with the maize recorded cropping areas in the main producing regions, limitations by different factors on total production are shown in Table 3. In NCS and HS, precipitation was the main limiting factor on total maize production among the three factors, and the regional limitations were 7051.56 × 10^4 t and 6840.04 × 10^4 t, respectively. Compared with Y_p, total maize production was reduced by 47.6% and 52.7% by precipitation in NCS and HS. However, the yield limitation due to soil conditions (1020.98 × 10^4 t, 6.9%) was lower than that due to technology & management (2424.24 × 10^4 t, 16.4%) in NCS, while opposite results were found in HS, where the limitation due to soil was 337.18 × 10^4 t and 2.6% greater than limitation due to technology & management. In SCM, technology & management was the most important limiting factor (1295.72 × 10^4 t and 39.3%), followed by precipitation (613.80 × 10^4 t and 18.6%), and soil (219.62 × 10^4 t and 6.7%). In all three main cropping regions, the limitation by each factor on total production in the high-stable zone was the highest among the four types of zones.

4. Discussion

Studies have shown that, under climate change, both regional and global food production was affected by changed agro-climatic conditions (Trnka et al., 2011). Without adaptation to increasing temperatures, losses in aggregate crop production are expected (Challinor et al., 2014). In addition, studies also report that yield stability may be reduced because of the increased probability, frequency, and severity of possible meteorological disasters (Lesk et al., 2016). Based on recorded county-level averages and CVs of maize yield from 1981 to 2010, the three main cropping regions in China were divided into four zone types with regard to yield and yield stability (high-stable, low-stable, high-unstable, and low-unstable). The highest ratio of cropping area in the high-stable zone was 45.9% in HS, while the ratio in NCS was 42.3%. In SCM, the ratio of maize cropping areas in high-stable zone was the lowest among the three regions. A similar distribution of high maize yield plots was also found using the surveyed methods in China, which reported that most high-yield plots were located in NCS and HS (Chen et al., 2012). The distribution of high-stable zones was in accordance with the suitable cropping zones diagnosed by the 'Divisions of advantage maize cropping zones in China (2008–2015)', produced by the

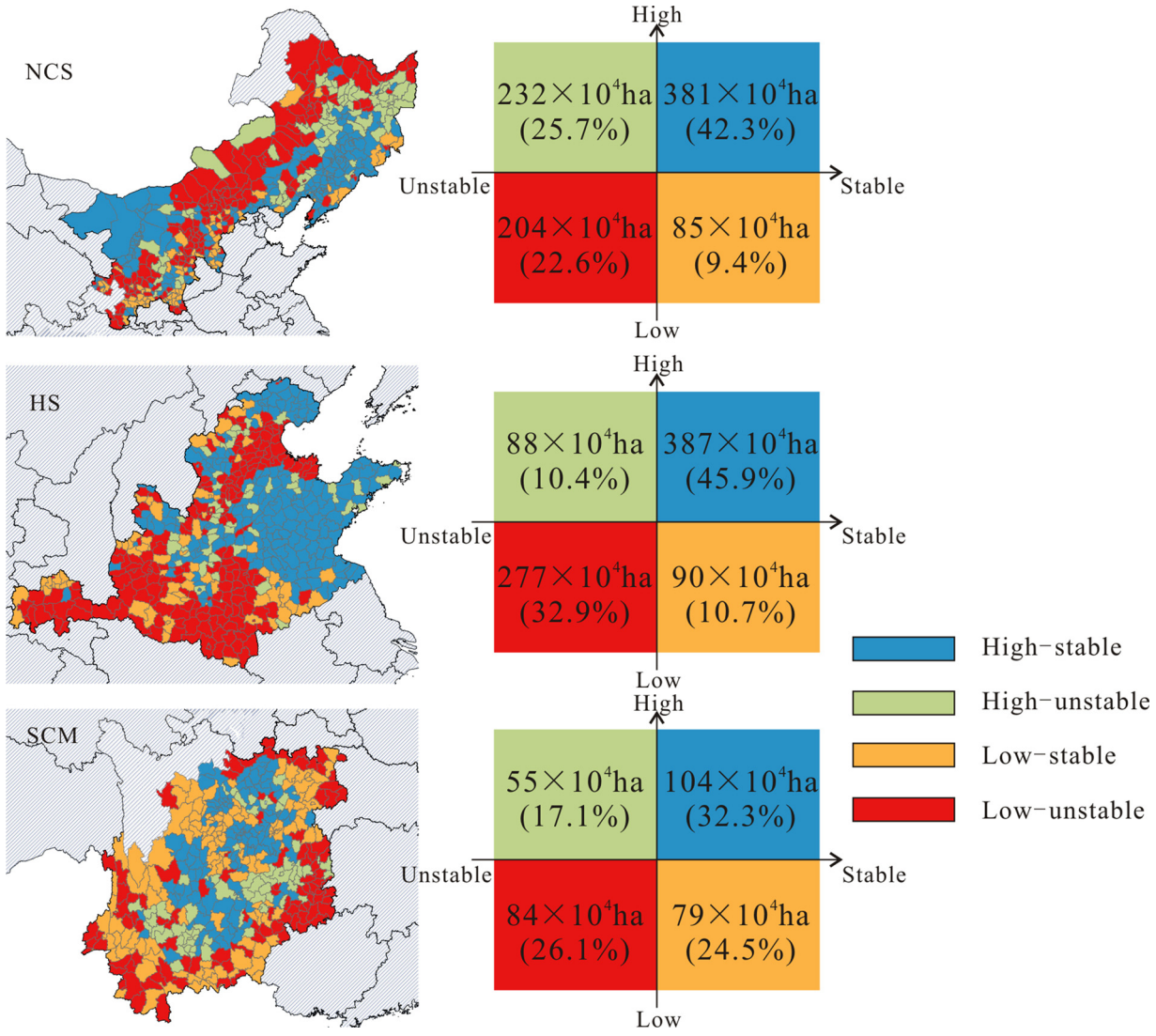

Fig. 4. Distributions and areas of maize high-stable zones for recorded yield in the three main cropping regions in China, 1981-2010. The four types of yield and yield stability zones (high-stable, high-unstable, low-stable and low-unstable) are shown in blue, green, yellow, and red, respectively. NCS, HS, and SCM indicate the North China spring maize region, the Huanghuaihai summer maize region, and the Southwest China mountain maize region, respectively. [Colour figure can be viewed online].

Chinese government. However, higher maize yield stability was found in the SCM region, which could be attributed to the ~20% lower average maize yield than in other regions and to the highest ratio of cropping area in a low-stable zone.

Since there are different environmental and agricultural productive conditions in China, the factors limiting maize yield and their limiting effects should be different in different areas. Yield and yield stability gaps between different simulated yields under different limiting conditions and the recorded yields reflected the limiting effects resulting from different factors (Cassman et al., 2003; Liu et al., 2016a). In this study, the quantified differences in averages and CVs between Y_p and Y_{pw}, Y_{pw} and Y_{pws}, and Y_{pws} and Y_a were selected to represent the limitations imposed on maize yield by precipitation, soil, and technology & managements in each region from 1981 to 2010. In NCS and HS, precipitation was the main limiting factor on both, yield averages (9436.97 kg ha^{-1} and 8114.21 kg ha^{-1}) and CV values (0.42 and 0.39), in all four types of yield and yield stability zones. In agreement with our own finding, Tao and Zhang (2010) found that water stress was one of major limitations for maize growth and productivity in northern and northeastern China. This suggests that improvement of irrigation practice is a promising strategy for improving maize yield and its stability in most parts of NCS and HS (Grassini et al., 2011; Tao and Zhang, 2010). However, precipitation is not the main limiting factor in the eastern regions of NCS, because these areas receive more than 500 mm precipitation during the growing season (Liu et al., 2012). Instead of precipitation, technology & management was the main limiting factor in SCM. These results are consistent with Liu et al (2017) and Tao et al. (2015), who reported that precipitation was the main limiting factor on maize yield except for southwest China, where average precipitation during the maize growing season reaches 653 mm; although, the limiting effect values were different. Additionally, the limitation by technology & management was the second most important limiting factor on both average maize yield and its stability in NCS. The limiting effects of technology & management on average maize yield were less than those of soil in high-stable and high-unstable zones in HS, where the yield can be improved by soil managements (Liu et al., 2016b). Because of the high fertility of soils in NCS, the maize belts in this region, together with those on the same latitude in America and Ukraine, have been called the 'Three Global Golden Maize Belts' of the world. In all three main cropping regions, the limiting effect of each factor on total maize production was the highest in high-stable zones among the four types of zones. In practice, fields in

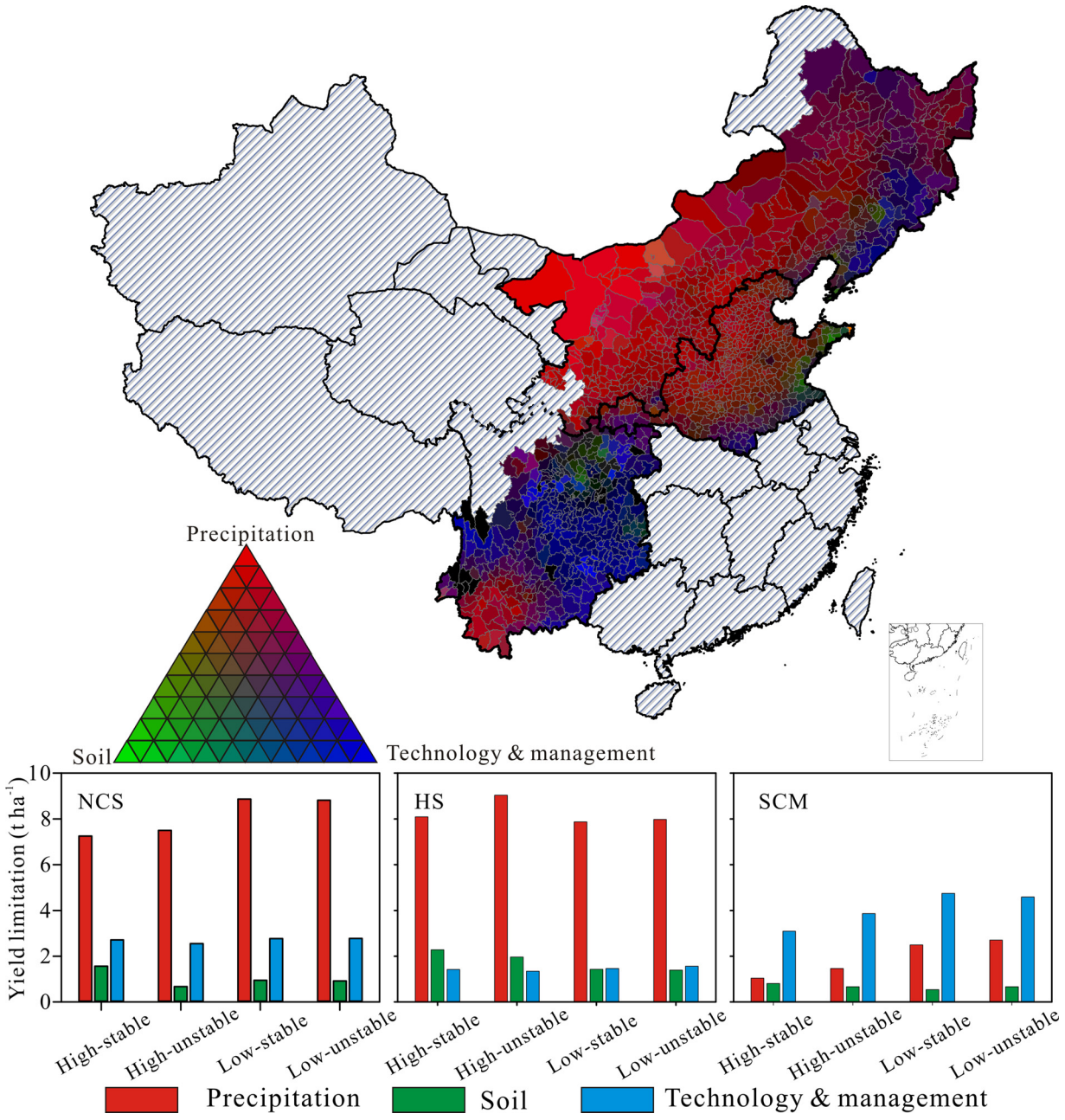

Fig. 5. Constraints by precipitation, soil, and technology & management on maize yield averages in the three main cropping regions in China. Red color indicated that precipitation was the primary constraint factor on average maize yield, green color indicated that soil was the primary constraint factor on average maize yield, and blue color indicated that technology & management was the primary constraint factor on average maize yield (The readers may also refer to the interpretation by color in the triangle legend). NCS, HS, and SCM indicate the North China spring maize region, the Huanghuaihai summer maize region, and the Southwest China mountain maize region, respectively. [Colour figure can be viewed online].

high-stable zones should receive more attention under climate change conditions in the future. However, the effect of each factor was not strictly independent, and there could be interaction effects by all three factors. The amount and timing of irrigation can offset limitation due to precipitation; while, advanced irrigation equipment and management can also improve water use efficiency to increase yields. Sufficient nutrient may compensate nutrient deficiencies in the soil, and integrated soil-crop system management approaches can also produce a higher maize yield with less fertilizer use (Chen et al., 2011).

We were able to investigate the distributions of recorded maize yield and yield stability in the three main maize cropping regions in China, as well as to quantify the constraints on maize yield, yield stability and the total production due to precipitation, soil, and technology & management in each region. However, our study is not exempt of limitations. A positive contributions by hybrids to yield improvement has been demonstrated by a number of studies (Challinor et al., 2016; Liu et al., 2013; Lv et al., 2015; Meng et al., 2016), but only one hybrid was used in each region in this study. Additionally, substantial improvement in agronomic management and technology improvement has also contributed to increasing maize yield. For example, plastic film mulching increased maize yield by reducing soil evaporation while increasing crop transpiration and soil temperature, as has been widely corroborated in regions where maize is grown as a spring crop in China (Liu et al., 2009). Because of the significantly increased optimal maize planting density, enhancing maize plant population with drip irrigation, precision sowing, and mechanical harvest have also contributed to

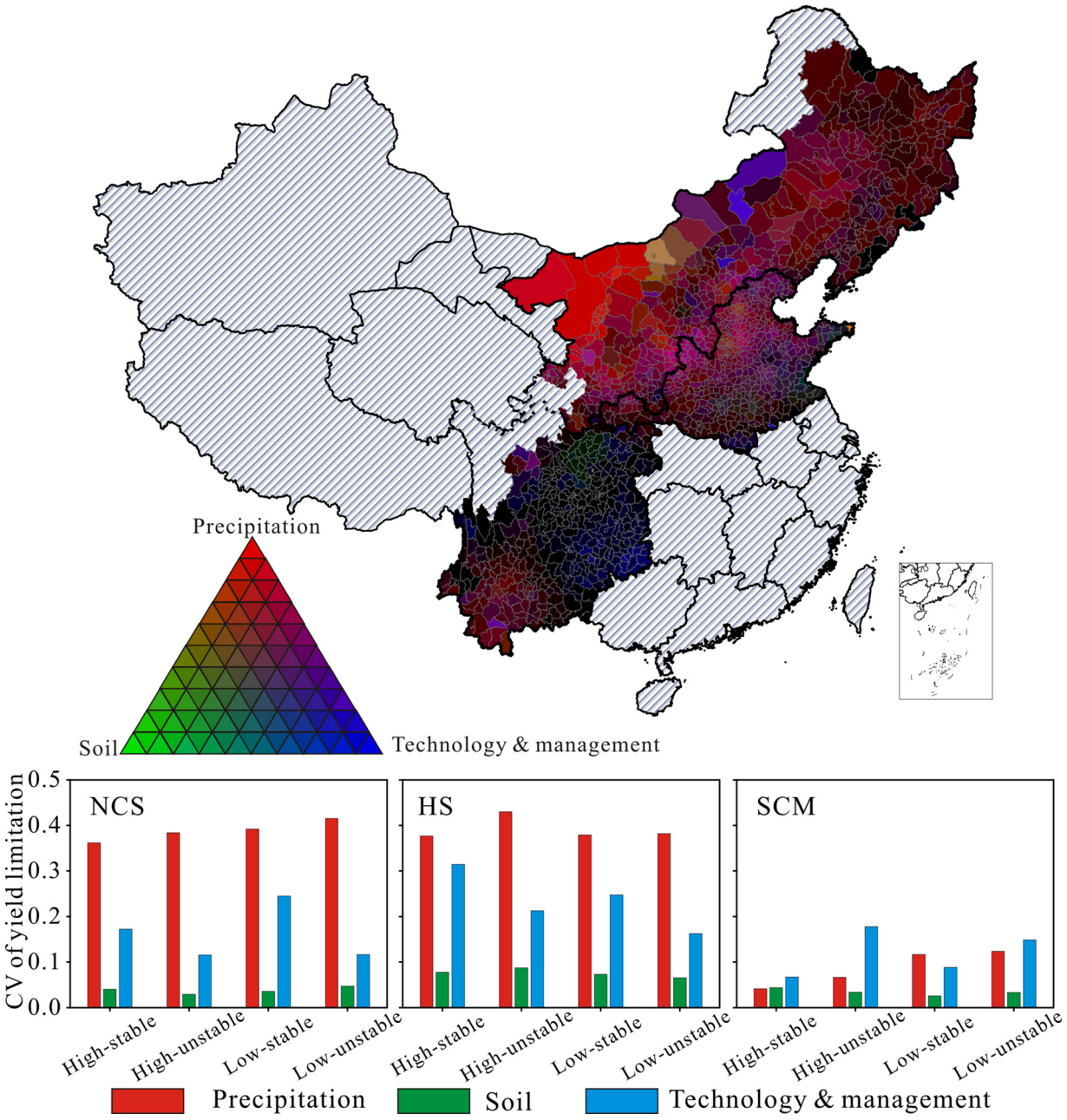

Fig. 6. Constraints by precipitation, soil, and technology & management on the coefficients of variations (CVs) of maize yield in the three main cropping regions in China. Red color indicated that precipitation was the primary constraint factor on the CVs of maize yield, green color indicated that soil was the primary constraint factor on the CVs of maize yield, and blue color indicated that technology & management was the primary constraint factor on the CVs of maize yield (The readers may also refer to the interpretation by color in the triangle legend). NCS, HS, and SCM indicate the North China spring maize region, the Huanghuaihai summer maize region, and the Southwest China mountain maize region, respectively. [Colour figure can be viewed online].

increased yield (Wang and Li, 2013). Therefore, further advances in seed genetics, biotechnology, agronomic management techniques and other agricultural technology may further boost maximum yields far beyond current levels (Licker et al., 2010). Furthermore, the county-level was the smallest level analyzed in our study; while, there were still differences among field plots in each county. The grading standards were also different and distributions of the four zone types were relative in each region. Although the actual maize cropping area surely was different each year, we consistently used an average cropping area for calculations. Despite these limitations, our study provides useful data on maize yields and factors affecting maize yield and yield stability in China.

5. Conclusions

In this study, based on recorded maize yield and simulated yield potential from 1981 to 2010, the distributions of maize yield and yield stability zones and constraints due to precipitation, soil, and technology & management on average yield, yield stability and total maize production were analyzed. County-level average recorded yields from 1981 to 2010 were 4624.26 kg ha^{-1}, 4718.32 kg ha^{-1} and 3880.44 kg ha^{-1} in NCS, HS and SCM, respectively. Meanwhile, the average CVs of actual yields were 0.40, 0.30 and 0.27 in NCS, HS and SCM, respectively. Comprehensive analysis of both, averages and CVs of actual maize yield, revealed that the highest ratio of cropping areas in high-stable zone was 45.9% in HS; while, the ratios in NCS and SCM were 42.3%

Table 3
Constrains by precipitation, soil and technology & management on total maize productions in the three main cropping regions.

Limiting factor	Limiting effect on the total production ($\times 10^4$ t)					Limiting percentage (%)
	High-stable	High-unstable	Low-stable	Low-unstable	Total	
North China Spring Maize Region						
Precipitation	2764.65	1737.29	753.80	1795.81	7051.56	47.6
Soil	596.02	156.67	80.88	187.41	1020.98	6.9
Technology & management	1033.15	590.47	235.17	565.45	2424.24	16.4
Huanghuaihai Summer Maize Region						
Precipitation	3126.61	794.60	708.04	2210.78	6840.04	52.7
Soil	882.04	172.68	128.85	386.26	1569.83	12.1
Technology & management	550.14	118.45	131.68	432.39	1232.65	9.5
Southwest China Mountain Maize Region						
Precipitation	108.30	80.67	197.40	227.42	613.80	18.6
Soil	84.16	36.65	42.54	56.27	219.62	6.7
Technology & management	321.68	213.11	375.10	385.83	1295.72	39.3

and 32.3%, respectively. Comparing the county-level Y_p, Y_{pw}, Y_{pws} and Y_a in the three regions, we found that precipitation was the most important limiting factor on both averages (56%, 9436.97 kg ha^{-1} and 53%, 8114.21 kg ha^{-1}) and CVs (0.42 and 0.39) of yield in all four yield and yield stability zones in NCS and HS; whereas, technology & management was the most important limiting factor in SCM (39%, 3934.87 kg ha^{-1}). Coupled with the actual maize cropping areas, total maize productions were limited by 47.6% and 52.7% by precipitation in NCS and HS, respectively. Nevertheless, the limiting effect by soil was lower than that by technology & management in NCS, while it was higher in HS. In SCM, technology & management was the most important limiting factor (1295.72 $\times$ 10^4 t and 39.3%), followed by precipitation (613.80 $\times$ 10^4 t and 18.6%) and soil (219.62 $\times$ 10^4 t and 6.7%). In all three main cropping regions, the limiting effect by each factor on total productions in the high-stable zone was the highest among the four zone types.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.eja.2018.07.003.

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